Journal of Volcanology and Geothermal Research, 50 (1992) 41–54
Elsevier Science Publishers B.V., Amsterdam

"Coherent intrusion complexes" in large basaltic volcanoes — a new structural model

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(Received January 7, 1991; revised and accepted July 30, 1991)

ABSTRACT

Walker, G.P.L., 1992. "Coherent intrusion complexes" in large basaltic volcanoes — a new structural model. In: K.G. Cox and P.E. Baker (Editors), Essays on Magmas and Other Earth Fluids (a Volume in Appreciation of Professor P.G. Harris). *J. Volcanol. Geotherm. Res.*, 50: 41–54

Highly concentrated "coherent intrusion complexes" consisting of thousands of small mafic intrusions occur in probably all major basaltic volcanoes and play an important role in volcano development. Magma excursions from the high-level chamber travel laterally along a surface of neutral buoyancy at the margin of a complex and cause the complex to grow. The limited distance, however, that narrow intrusions can propagate before becoming blocked causes complexes to be wedge like. *Intrusive-dike complexes* underlie rift zones, and asymmetric growth of the dike wedge causes rift zones of shield volcanoes to become non-collinear and may initiate a third rift zone in the obtuse angle. Downbowing of stress trajectories across complexes causes dikes to be non-vertical and results in axial subsidence. *Intrusive-sheet complexes* form instead of dike complexes in volcanic systems that have a restricted ability to expand laterally and accommodate intrusions by expanding vertically instead. Downbowing of stress trajectories causes sheets to be non-horizontal, and this combined with subsidence increasing toward the thicker part of the sheet wedge produces the inward and inwardly increasing dip that characterizes cone-sheet complexes. This mechanism for cone sheets differs considerably from previously proposed mechanisms. Successive injections of sheets at the top of a sheet complex probably offers the most efficient means of powering a high-intensity geothermal field such as the 5000 MW Grimsvotn system in Iceland.

It is inferred that similar mechanisms to those in major basaltic edifices operate in spreading ridges; study of basaltic edifices has the potential to contribute significantly to the understanding of spreading ridges.

Introduction

Complexes of mafic dikes or intrusive sheets containing thousands of members and having a high intrusion intensity (intrusions typically comprise > 40% of the rock) occur in the cores of many if not most major basaltic volcanoes and play an important role in development of the volcanoes.

The term "coherent" is here proposed for such complexes, because the intrusions are tightly packed together and display a high degree of parallelism, and the high intrusion intensity falls rapidly to near zero at the margins of the complexes.

The type example of a coherent dike complex is that of the eroded (1.8–2.8 Ma) Koolau lava-shield volcano on Oahu, Hawaii (Walker, 1986, 1987). At its widest, the complex is 7 km wide and contains an estimated 7400 dikes totalling > 4 km wide.

The type examples of coherent intrusive-sheet complexes are those in the deeply eroded 58–59 Ma Skye and Mull central volcanoes of the Hebridean Province (Emeleus, 1982). Harker (1904) mapped the distribution of

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sheets in and around the Cuillin Hills gabbroic intrusions is Skye, recognized the systematic centripetal dip toward a common focus, and named them "centrally inclined sheets". These and similar intrusions in Mull (Bailey et al., 1924) later came to be called cone sheets.

This paper recognizes that coherent complexes are seen in all investigated major basaltic volcanoes that are sufficiently deeply eroded to reveal them, considers the reasons why they form, discusses some of the consequences of their formation, and proposes a new model of emplacement of intrusions in large volcanoes. Aspects of the model have been published elsewhere (Walker, 1986, 1987, 1989, 1990).

Injection at surface of neutral buoyancy

An important feature in transects across the Koolau dike complex is that the intensity distribution is not Gaussian but has a "top hat" distribution; the existence of a plateau at an intensity value of about 65% was taken by Walker (1986) to imply that some mechanism operated to restrain entry of magma into the complex when the (roughly) 65% intensity value was attained.

The model proposed to explain this relationship envisages a gross density zonation, developing in basaltic volcanoes and controlling the internal plumbing system (Fig. 1). The coherent intrusion complex with its 65% complement of mostly non-vesicular and dense dikes, plus the prism of gabbroic to ultramafic intrusions and cumulate rocks underlying the magma chamber in the core of the volcano, have an overall bulk-rock density greater than that of common non-vesicular basaltic magmas. The remainder of the volcanic edifice consists mainly of lavas which, because of their high porosity, have a bulk-rock density less than that of common non-vesicular magmas. Surfaces of neutral buoyancy (cf. level of neutral buoyancy, Ryan, 1987) thus exist between these zones. Magma that resides in or travels along these surfaces is in a state of gravitational equilibrium (Walker, 1989).

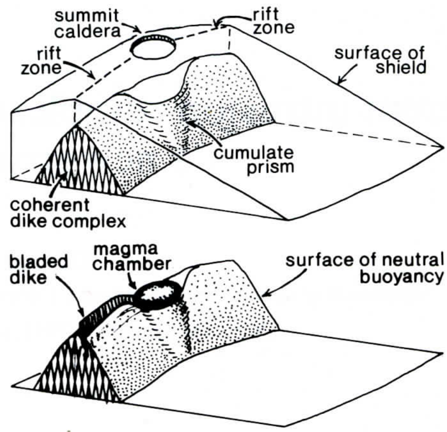

Fig. 1. Schematic view of the structure of a shield volcano consisting of a coherent dike complex and cumulate prism denser than common non-vesicular mafic magmas, and an edifice of vesicular lava flows less dense than common non-vesicular magmas. A surface of neutral buoyancy separates the two density zones; the magma chamber resides on this surface, and laterally propagated bladed dikes straddle it.

Dike-complex growth

It is inferred that coherent dike complexes develop at the peak of a volcano's activity when the magma-supply rate is at its maximum. Kilauea and Mauna Loa in Hawaii exemplify lava-shield volcanoes at their peak. Several decades of volcano monitoring have led to the concept that each volcano has a high-level magma chamber wherein magma is stored, and from which magma excursions take place from time to time, generally involving lateral flow into rift zones (Decker, 1987; Ryan, 1987). These excursions add dikes to the coherent complex.

The surface expression of a dike complex is a rift zone. Rift zones, well displayed on Kilauea and Mauna Loa, are narrow zones along which ground cracking occurs as dikes are injected, and in which fissure eruptions occur. Geophysical studies indicate that rift zones are underlain by rocks, presumed to be intrusions, having a high P-wave velocity and a relatively high density (giving positive gravity anomalies) (Furumoto, 1978). Confirmation that Kilauea's east rift zone overlies a coherent dike complex came recently when a 2-km-deep cored hole (SOH 4) was drilled 35 km downrift from the summit. In the 982-m depth interval, 579 to 1561 m, intersected dikes totalled 53% of that interval (Trusdell et al., 1990).

In the <200-year historic period, Kilauea and Mauna Loa have each experienced about 30 fissure eruptions which, it is inferred, involved the injection of about 30 dikes. A considerable number of non-eruptive magma excursions are known to have occurred in Kilauea in the same period, many of which also generated dikes (Dzurisin et al., 1984; Klein et al., 1987).

The whole magma delivery and distribution system of such volcanoes favors repeated magma excursions into rift zones. Magma freshly arrived from the mantle source collects in the high-level magma chamber. The chamber swells, and eventually wall rupture occurs and a magma excursion takes place. Preferential injection as a bladed dike in the margin of a rift zone is strongly favored because of the neutral buoyancy condition there; it is also favored by the existence of planes of weakness along the margins of earlier dikes and, if the frequency of magma excursion is high, by channeling of the magma along the still hot and mechanically weak centers of preceding dikes (Fig. 2).

The system is a self-sustaining one and, indeed, the density zonation that determines the position of neutral buoyancy becomes accentuated with time. In particular, the level of neutral buoyancy where the high-level magma chamber is situated becomes accentuated by the settling of olivine and other mafic crystals from the magma to produce extremely dense cumulate rocks such as dunite. For an oceanic island volcano this chamber will likely be initially situated high in the oceanic crust, but as the cumulate prism grows, the level of neutral

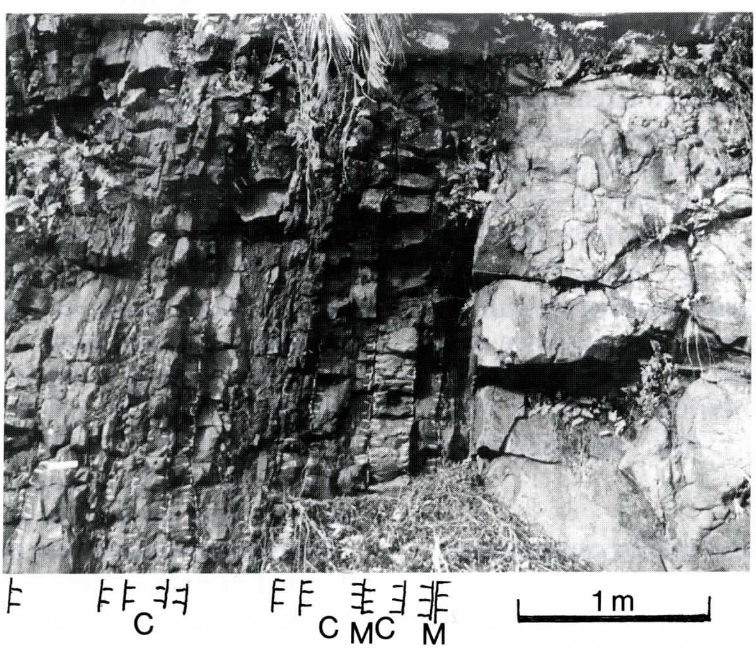

Fig. 2. Coherent dike complex in roadcut at Fagalatua in Tutuila, American Samoa. The view is 4 m wide and includes more than 9 dykes. Dike margins shown by hatched lines (hatches face inward). Note examples of dike (*C*) injected along center, and (*M*) injected along margin, of earlier dike.

buoyancy and hence the magma chamber ascends to keep pace with volcano growth.

It is speculated that the position of the first-intruded dikes is likely to be determined by structure in the subvolcanic basement rocks. A small cluster of dikes may then suffice to initiate a coherent complex. As more dikes are attracted to this gravitationally favorable site the density zonation becomes accentuated, and growth of the complex then proceeds apace. Down-rift extension of dikes can lengthen a rift zone and cause elongation of the volcano.

Note that in this model the blade-like form, lateral propagation, and position of a dike relative to a coherent complex are determined by the existence of a surface of neutral buoyancy, but the orientation of the plane of a dike is determined by the stress pattern.

In the model applied to Hawaiian volcanoes by Fiske and Jackson (1972), the blade-like form, lateral propagation, position and orientation of a dike were all attributed to a stress pattern operating in a volcanic edifice as a consequence of the shape and size of the volcano. These two models are alternatives but are not mutually exclusive.

An important role of a coherent complex is to partition magma between intrusives and surface extrusives. Magma from the source region accumulates in the high-level magma chamber and batches released from the chamber travel laterally along a neutral buoyancy surface as bladed dikes straddling that surface. It may be that eruption occurs only when a part of that magma, either in the chamber or in a dike, reaches a sufficiently high level or acquires a sufficiently high gas content to vesiculate.

Injection of dike wedges and its consequences

Additions to a dike complex in a given time construct a wedge that is widest near the high-level magma chamber and narrows downrift. Evidence for this comes from historic fissure eruptions of Kilauea and Mauna Loa volcanoes which for each volcano exceed 30 km at the summit and decrease to one at a distance of 17–60 km downrift (Walker, 1988).

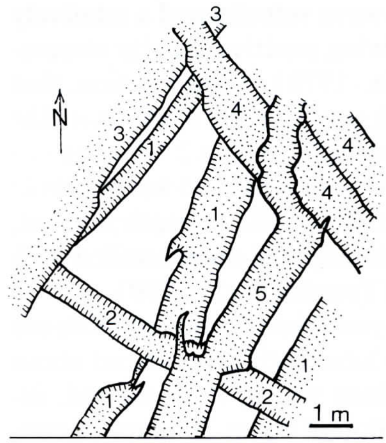

Fig. 3. A small section of coastal exposure at Fonte da Areia on Porto Santo (Madeira) showing orthogonal dike intersections in plan view. Note the alternation of dike strikes *1-2-3-4-5*. Dikes stippled, and dike margins shown by hatched lines (hatches face inward).

Generation of a dike wedge results from the very limited ability of narrow dikes to extend laterally. As a dike is injected, a layer of solidified rock rapidly forms on either wall and when these layers meet in the middle the dike becomes blocked (Bruce and Huppert, 1989). Modeling shows that narrow (1 m) dikes may become blocked in only 9–11 hours depending on the countryrock temperature. Wilson and Head (1988) confirm the rapidity with which narrow dikes (such as predominate in the Koolau complex) solidify.

A factor tending to oppose construction of a dike wedge is a general downrift increase in dike width. In the Koolau volcano the average dike width is 0.75 m near the Kailua caldera and increases to 1.25 m at 15 km downrift. Combining the two effects, the number of dikes injected in a given time halves in 3.5 to 12.5 km downrift, whereas the median dike width doubles in 20 km; the total width of dikes injected in a given time thus decreases downrift and halves in 4 to 33 km.

When a dike wedge is injected having a wide end that may grow to several kilometers wide, an important consequence is that extensional stresses are set up adjacent to the wide end of the wedge. These stresses may be relieved by the injection of dikes approximately orthogonal to the length of the wedge. Orthogonal dikes are a characteristic feature of dike complexes in the vicinity of the volcanic center (Fig. 3). Commonly an alternation of the two trends occurs and is easily explained by the above mechanism.

Asymmetric growth of coherent complexes

Surfaces of neutral buoyancy exist on both sides of a coherent dike complex, but a small asymmetry in the plumbing system or the strength of the volcano may cause preferential growth of one side of the complex.

Asymmetric growth appears to be actively occurring on Mauna Loa's south west rift zone where, as pointed out by Lipman (1980) and Lipman et al. (1990), there is good evidence that the axis of the rift zone migrated laterally; similarly for Kilauea's east rift zone (Swanson et al., 1976; Fig. 4).

An important consequence of asymmetric growth is to cause rotation of crustal blocks and to concentrate extensional stresses on the actively growing side. Rift zones that were initially collinear become non-collinear (Fig. 5) and the extensional stresses are relieved by injection of orthogonal dikes (Fig. 3) and may eventually lead to the development of a third rift zone in the obtuse angle between the two original zones. Haleakala is an example of a volcano in Hawaii that has three rift zones, and Mauna Loa has non-collinear rift zones with what is regarded as a radial fissure swarm in the obtuse angle (Lockwood and Lipman, 1987). Three eruptions (in 1843, 1859 and 1877) occurred in this swarm in historic time. This mechanism is somewhat different from that proposed by Rubin (1990).

By a similar mechanism but involving a change in the side of the dike complex on which preferred growth occurs, two non-collinear rift zones can become straightened. This seems to be actively happening on Kilauea (Fig. 4). Lateral migrations of an active rift zone could generate dike complexes that wander laterally through the volcano (Fig. 6).

It may be suspected that asymmetric growth of a dike complex in a large oceanic-island vol-

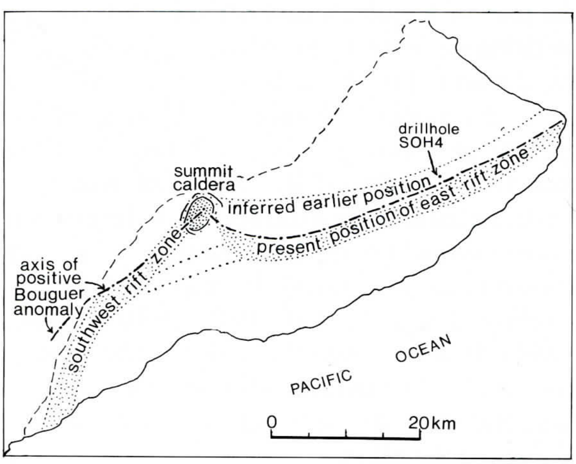

Fig. 4. Sketch map of Kilauea volcano, Hawaii, showing inferred earlier and present positions of rift zones. Asymmetric growth is tending to straighten the two rift zones. Cored drillhole SOH4 intersected dikes totalling 640 m thick in 2 km.

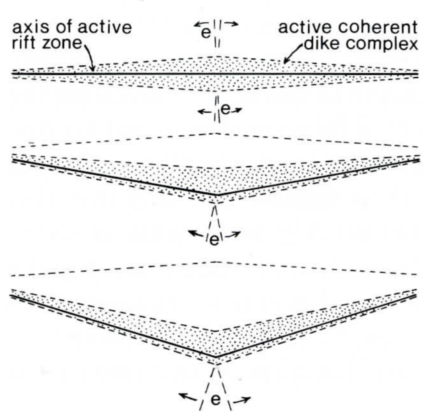

Fig. 5. Plan view (above) of two collinear rift zones and underlying wedge-like dike complex showing (below) how asymmetric growth of the latter can cause the two rift zones to become non-collinear and can set up extensional stresses (e) relieved by the injection of orthogonal dikes and development of a third rift zone.

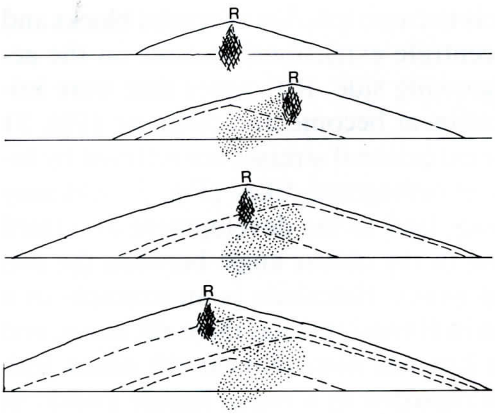

Fig. 6. Development of a major volcano (schematically in cross section) showing how, with asymmetric growth, the active rift zone (R) may vary in position and the coherent dike complex (earlier formed parts stippled) may develop an irregular form. Stresses resulting from asymmetric growth may be relieved by injection of orthogonal intrusions or by faulting.

cano will sometimes lead to catastrophic failure of part of the edifice on the side of active growth, as has happened to most of the Hawaiian volcanoes (Moore et al., 1989) and may yet happen to the south side of Kilauea.

Non-verticality of dikes

Most of the dikes in the Koolau complex are non-vertical. The dike dip varies from 90° to under 30° and the median dip is 75° (Walker, 1987). The dikes apparently form a single population: those that dip at 30° constitute the low-angle "tail" of this population and for this reason it is considered appropriate to call them dikes despite their shallow dip. It is true that many dikes that are highly irregular in shape have short sections of very shallow dip, but the low-angle "tail" consists of true low-angle dikes as is shown by the steep attitude of their dilation vector (the direction of opening of the dike).

Dikes in investigated complexes elsewhere are also non-vertical, for example, in American Samoa, Ponape (Caroline Islands) and Madeira as well as those intersected by a drillhole low on Kilauea's east rift zone. This non-verticality is evidently a characteristic feature of coherent dike complexes (Fig. 7).

The preferred explanation for non-verticality is that stress trajectories are downbowed into a non-horizontal orientation across coherent complexes (Fig. 8a) and the clear tendency for dikes at the margins of a complex to dip outward is attributable to a more or less symmetrical downbowing of stress trajectories on either side of a complex.

A consequence of non-verticality is that injection of a dike involves a vertical as well as a horizontal displacement of the countryrock. On average, each Koolau dike has a vertical displacement of 30 cm for each meter of horizontal dilation. This vertical displacement may be the origin of the graben that developed at Kapoho low on Kilauea's rift zone prior to and during the eruption of 1960 (Richter et al., 1970).

In a dike complex in which the dikes predominantly dip outward on either side, injection of the dikes could produce substantial relative and actual subsidence of the middle of the complex amounting to as much as about 1 km per 3 km horizontal dilation (Fig. 8a).

An unexpectedly great subsidence, presumably localized in the rift zone, has occurred in the part of Kilauea's east rift zone intersected by drillhole SOH 4 (Trusdell et al., 1990) and has depressed the boundary between subaerial and subaqueous volcanics to 1260 m below present sea level. General subsidence in the past two decades of the whole of Kilauea's caldera area and the axial region of the east rift zone (even where no dike-injection events are known to have occurred) is well established by leveling (Swanson et al., 1976; Delaney et al., 1989). It is supposed that this general subsidence is due to isostatic adjustments. It would have the effect of contributing to the non-verticality of the dikes.

Decline of activity

With a significant decline in magma supply rate, the high-level magma chamber of a basal-

Fig. 7. Cliff section on one of the Mokulua Islands of the coherent dike complex of Koolau volcano, Oahu, showing non-verticality of dikes. Dikes comprise 80% of this 5.5 m wide view. About half dip steeply to the left and about half to the right.

tic volcano solidifies, the rift zones cool, and the well-organized magma-distribution system breaks down. Although some magma excursions may still take place along the neutral buoyancy surfaces to continue growth of the coherent dike complexes, excursions increasingly fail to be guided by the gross density zonation.

Factors that may contribute to this failure are a generally deeper exsolution of gases from the more volatile-rich, more-alkalic magma (so changing the density and increasing the buoyancy of the magma), a generally higher ascent rate (giving the magma less time to seek out the gravitationally most favorable pathway), and a distinct increase in viscosity (making the

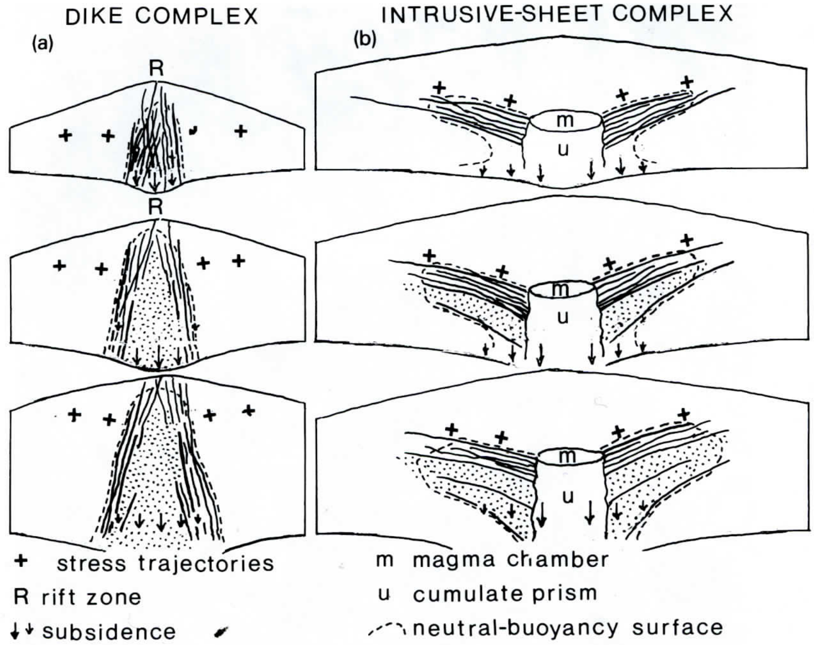

Fig. 8. Schematic sections showing stages in the growth of a coherent dike complex (a) and a coherent intrusive-sheet complex (b); earlier formed parts stippled. The non-verticality or non-horizontality of the intrusions is attributed to a downbowing of the stress trajectories, with a contribution (especially marked in sheet complexes) from differential subsidence. These diagrams illustrate symmetrical growth; asymmetric growth is probably more common.

magma less responsive to small variations in bulk-rock density).

Well-documented examples occur in the Hawaiian islands of the changes that accompany a decline. Mauna Kea for example shows a wide scatter of eruptive vents (Macdonald, 1945) overprinted on the shield volcano such that the original rift zones are barely discernable. In addition, the summit caldera has been infilled (Porter, 1972) and the volcano slopes have been considerably steepened. On the Koolau volcano, lines of "rejuvenation-stage" vents are almost orthogonal to the main rift zone and have an orientation that appears to be determined by a regional stress pattern (Walker, 1990).

Examples of coherent dike complexes

In addition to Koolau, West Maui volcano in Hawaii contains a coherent dike complex (Diller, 1982) and the East Molokai volcano (Stearns and G.A. Macdonald, 1947) probably contains one although intensity values are lacking. The 2000-m-deep hole SOH 4 recently drilled in Kilauea's lower east rift zone entered a dike complex and intersected a total dike thickness of 640 m.

Coherent dike complexes appear to be common in large eroded oceanic volcanoes elsewhere. Recently documented examples are Ponape (Pohnpei) in the Caroline Islands (Spengler and Walker, in prep.), Tutuila in American Samoa (Stearns, 1944; Walker and Eyre, in prep.), and Madeira (Walker, in prep.). In all three the intensity considerably exceeds 40%.

Rift zones and dike swarms are common in Iceland, but most dike swarms at the level of exposure are not sufficiently concentrated to be regarded as coherent complexes. Probable examples of coherent complexes occur associated with the central volcanoes of Thingmuli (Carmichael, 1964) and Breiddalur. That of

Breiddalur attains an intensity of only 13% in surface outcrops at the head of Reydarfjordur, some 20 km downrift from the volcanic center (Walker, 1974) but a scientific drillhole 1919 m deep sited in this swarm intersected dikes totalling 41% of the total rock (Robinson et al., 1982).

Coherent intrusive-sheet complexes

A proportion, probably more than half, of major basaltic volcanoes contain coherent intrusive-sheet complexes instead of dike complexes. Systematic measurements of intrusion intensity have seldom been made, but so far as is known coherent sheet complexes have about the same intensity, and a similar degree of parallelism, as coherent dike complexes (Fig. 8b).

A simple explanation is now proposed for the occurrence in some volcanoes of intrusive-sheet complexes in place of dike complexes (Fig. 9). It is that a dike complex can be injected only if crustal blocks on either side are free to move apart sufficiently to accommodate it; otherwise, an intrusive-sheet complex will form since the volcano is then free only to expand vertically to accommodate magma injections.

Intrusive-sheet complexes are favored in slow spreading-ridge situations as in Iceland. They develop in central volcanoes which are the locus of magma supply (Fig. 9d). Global plate motions constrain the rate at which these volcanoes can widen, but the rate at which intrusions are injected is independently deter-

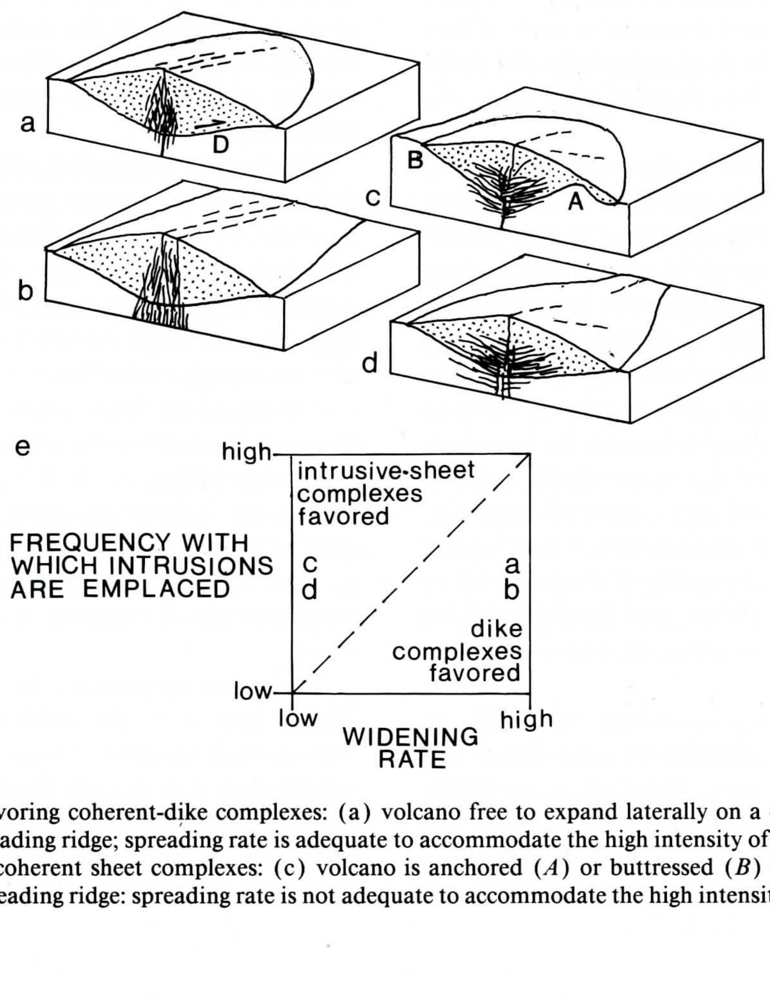

Fig. 9. Conditions favoring coherent-dike complexes: (a) volcano free to expand laterally on a decollement (*D*): (b) volcano on a fast-spreading ridge; spreading rate is adequate to accommodate the high intensity of intrusive activity. Conditions favoring coherent sheet complexes: (c) volcano is anchored (*A*) or buttressed (*B*) by other edifices; (d) volcano on a slow-spreading ridge: spreading rate is not adequate to accommodate the high intensity of intrusive activity.

mined by the intensity of the local thermal anomaly.

Intrusive-sheet complexes are favored in isolated volcanic edifices (Fig. 9c) if the edifice lacks an underlying detachment surface or decollement (as envisaged by Nakamura, 1980) on which one or both sides of the volcano can slide easily, or if the edifice is effectively anchored by earlier edifices.

The concept of cone sheets

Harker (1904) published a classic account of the great swarm of centrally inclined mafic intrusive sheets found in and around the Cuillin Hills volcanic center of Skye in the Hebridean Province. He demonstrated that the dip of the sheets increases inward from about 20° on the periphery of the complex to about 45° near the focus. The countryrock into which the sheets were emplaced consists in part of layered gabbros and the sheets generally dip in the same direction as, but more steeply than, the layering.

Bailey et al. (1924) in their classic study of the eroded Mull volcano, also in the Hebridean Province, found swarms of sheets similar in character to those of Skye and called them "cone sheets". In this they were influenced by theoretical studies by Anderson (1936) who related the inverted-conical form of the sheets to excess magmatic pressure in a magma chamber. Roof failure occurred on inverted-cone fractures. The term "cone sheet" came to have a genetic as well as a geometric connotation. Modifications to Anderson's mechanism have since been proposed by Robson and Barr (1964), Roberts (1970), and Phillips (1974) but they retain the essential features of Anderson's model.

The author's opinion is that "centrally inclined sheet" is preferable to cone sheet: this partly because the cone-like form is an attribute of the whole set of sheets rather than any one individual member, and partly because a specific mechanism of origin is implicit in the name of "cone sheet". For the majority of examples, the particular mechanism is not accepted by the author.

The following critical facts are highly relevant to the origin of cone sheets but have seldom been investigated:

(a) To what extent is the dip original, or caused by subsequent tilting?
(b) To what extent is tilting a direct consequence of intrusion formation?
(c) Is the dilation vector (direction of opening) normal to the plane of intrusion?

Observations in southeastern Iceland (Walker, 1975) show that a component of the dip (about 10 to 20°) of the sheets there is original, this being the angle by which the sheets cut across the countryrock lava flows. Significant tilting involving both sheets and lava flows also occurred by an amount that tends to increase as the intrusion intensity increases. Intensity values are locally high and are similar to those in the Koolau dike complex (Fig. 10).

Injection of a coherent sheet complex as for dike complexes should generate a wedge-like assemblage of sheets which will cause rotation of blocks on either side. Considerations of isostasy require that most of the space for the high-density sheet complex will come from a downwarping of the floor rocks and only a minor component from uptilting of roof rocks. Some at least of the dip of the sheets will result from this tilting. As with coherent dike complexes, extensional stresses set up near the wide part of the wedge should be relieved by the injection of a swarm of orthogonal intrusions there that may be approximately radial in plan view.

The most impressive intrusive-sheet complexes known to the author occur alongside Vatnajokull ice sheet in southeastern Iceland, where they cut mainly hyaloclastites (attributed to intraglacial eruptions). Evidence is that some sheets intruded at a shallow (several hundred meters) depth in the hyaloclastite.

Fig. 10. Coherent intrusive sheet swarm in the southeastern wall of Rjupnadalur off Kalfafellsdalur in southeastern Iceland. Where, as in this photograph, the intrusion intensity is very high (85%), the dip of the sheets is also high (60°). Average sheet width 70 cm.

The density contrast between hyaloclastites and intrusive rock is considerable. Wedge-like gabbro intrusions also occur in this area (Annels, 1967; Newman, 1967) and may be of confluent-sheet origin in which successive sheets were injected into preceding sheets that were still hot.

Heat transfer in the Grimsvotn geothermal system

Coherent dike complexes can grow on either side, whereas in coherent sheet complexes the neutral buoyancy surface at the top is a more favorable position for sheet injection. One possible consequence is now considered.

Current injection of a coherent sheet swarm into hyaloclastites could account for the remarkably intense geothermal system, with an estimated power output of 5000 MW, that is centered at Grimsvotn in the Vatnajokull (Bjornsson, 1988). The transfer of thermal energy from magma to groundwater on this scale requires especially favorable conditions.

If the structure of Grimsvotn is broadly similar to that in southeastern Iceland, and if frequent injections at shallow depth of narrow intrusive sheets occur at the top of a coherent complex into hyaloclastites with a high water table, then conditions for heat exchange from magma into groundwater are ideal and could readily explain the high power output.

Examples of coherent intrusive-sheet complexes

Coherent intrusive-sheet ("cone-sheet") complexes have been described from Ardnamurchan (Richey and Thomas, 1930) and Carlingford (Richey, 1932) as well as Skye and Mull in the Hebridean Province. Similar complexes occur in many central volcanoes in Iceland, for example, Setberg (Sigurdsson, 1966), Reykjdalur (Johannesson, 1975) Geitafell (Fridleifsson, 1983), Vidbordsfjall (Annels, 1967; Newman, 1967), Skalafellshnuta, Rjupnadalur (off Kalfafellsdalur; Fig. 10) and Fellsfjall (Walker, 1975) in Iceland. Many intrusions thought to be low-angle sheets were intersected by geothermal drillholes in the Hengill volcano in southwestern iceland (Franzson and Sigvaldason, 1985). The most recent studies of an Icelandic sheet swarm, including a model of sheet-swarm formation, were by Gautneb et al. (1989) and Gudmundsson (1990).

A sill swarm occurs in the deeply eroded Piton de les Neiges volcano on Reunion (Upton and Wadsworth, 1970), and a sheet swarm, part of which has been rotated by up to 40°, occurs in La Palma, Canary Islands (Staudigel and Schmincke, 1984; Staudigel et al., 1986). McDougall et al. (1981) describe a cone-sheet swarm from Lord Howe Island in the Tasman Sea. A swarm of sheets comprising 40% of the 767 m total of igneous rocks was intersected by a scientific drillhole in Bermuda (Aumento and Ade-Hall, 1973; Rice et al., 1980).

The shield volcanoes of the Galapagos and also Kauai volcano in Hawaii lack clearly defined rift zones and tend to a circular plan form. It is suspected that they may contain intrusive-sheet complexes (cf. Cullen et al., 1987).

Discussion

This paper recognizes that high-intensity (>40%) complexes of small mafic intrusions are a normal and possibly invariable component of large basaltic volcanoes; it satisfies a perceived need to distinguish high-intensity complexes from low- to moderate-intensity swarms and presents a new view of the significance and origin of the high-intensity structures. It presents a dynamic model for orthogonal dike intersections and the formation of non-collinear (from initially collinear) rift zones. It sees coherent complexes as playing a vital if passive role in the marshalling of magma into different parts of a volcano and in partitioning this magma between intrusives and surface lavas.

It equates for the first time dike complexes and intrusive-sheet (cone-sheet) complexes as manifestations of the same process — the injection of a great volume of intrusive magma at a high modulation frequency along a neutral buoyancy surface — in the contrasted tectonic settings of unrestricted and restricted volcano widening and, in so doing, presents an alternative view of the origin of mafic cone sheets.

The most impressive coherent complexes comprise the "sheeted-dike" complexes of ophiolites, an important component of the oceanic crust formed by spreading in oceanic spreading ridges. Dynamic models have been proposed (for example, Macdonald, 1986) that satisfy the thermal constraints but in general do not consider the possible importance of a surface of neutral buoyancy in determining the buildup of the sheeted complex or in partitioning the magma between intrusives and pillow lava. The density values of pillow lava and dikes relative to magma in the underwater environment may, however, be different from corresponding values in volcanoes on land.

Existing models also do not acknowledge the possibility that intrusions may be emplaced either as low-angle sheets or high-angle dikes according to the spreading rate, or that the emplacement of the former probably always results in tilting and possibly results in faulting such as characterizes slow-spreading ridges.

Acknowledgements

I am indebted to Dr. Peter Harris for his friendship over four decades, the University of Hawaii Water Resources Research Center for funding fieldwork on Ponapei, Paul Eyre and the U.S. Geological Survey for funding fieldwork in American Samoa, the Jagger Bequest Fund for funding fieldwork in Madeira, and the University of Iceland for funding travel to an intrusive-sheet complex in Southeast Iceland.

School of Ocean and Earth Science and Technology Contribution number 2756.

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